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SUPPLEMENT 10

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APOLLO 10 MISSION REPORT
SUPPLEMENT 10

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ENTRY POSTFLIGHT ANALYSIS

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ENTRY POSTFLIGHT ANALYSIS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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PROJECT APOLLO

APOLLO 10 ENTRY POSTFLIGHT ANALYSIS

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APOLLO 10 ENTRY POSTFLIGHT ANALYSIS

1. INTRODUCTION AND SUMMARY

The objective of this report is to present an evaluation of the operation of the Apollo 10 entry guidance, navigation, and control system (GNCS), the entry monitoring plan, and a reconstruction of the entry trajectory utilizing the telemetry tape data. This report has been prepared as Supplement 10 to the Apollo 10 Mission Report (MSC-00126).

The data obtained from the onboard telemetry tape indicated that the GNCS performed as expected. The crew was ahead of the entry time line, so they performed several of the monitoring functions prior to the scheduled time. The reconstruction of the EMS scroll pattern trace indicated that the GNCS performed well within the bounds imposed by the monitoring plan.

Postflight evaluation of the operation of the Apollo 10 command module computer (CMC), during entry, indicates that the computer performed properly throughout entry. The primary evaluation was through comparisons of parameters generated by a CMC simulation with those parameters which were computed by the actual CMC and recorded on telemetry (TM) tape during the flight. Accelerometer data from the TM tape were utilized in the CMC simulation to provide the same input data that was used to drive the onboard computer. This comparison indicated the following: (1) the roll commands were identical except for the last 40 seconds of the trajectory, and (2) the time of the guidance logic sequencing was identical. The predicted trajectories during the huntest phase agreed within 10 nautical miles. The Display and Keyboard (DSKY) displays of the predicted entry conditions were in good agreement with the actual entry parameters. The onboard CMC computer position at the time of drogue deployment was 164.65 degrees west and 15.07 degrees south. The simulation Command Module (CM) position at drogue deployment was 164.65 degrees west and 15.07 degrees south.

Section 2 presents the entry state vectors used in the postflight analysis. The entry state vector recorded on the TM tape was used in the CMC evaluation while the 21-day Best Estimate Trajectory (BET) entry state vector was used in the trajectory reconstruction.

Section 3 presents the program sequencing and a discussion of the significant events occuring during each program. The data calculated by the CMC and recorded on the TM tape are discussed and compared to corresponding data obtained from postflight simulations.

Section 4 presents an evaluation of the entry monitoring plan. This section provides a chronological sequence of events of crew operations in the process of monitoring entry. Data is presented which indicates what the crew observed in real time via the DSKY displays, and how they responded in the process of monitoring the entry.

Section 5 describes the trajectory reconstruction and presents the entry parameters and the method of trajectory reconstruction.

Section 6 presents an evaluation of the entry monitor system (EMS) and the reaction control system (RCS) propellant consumption.

2. ENTRY CONDITIONS

The entry state vectors used for the Apollo 10 postflight analysis were obtained from two sources: (1) the 21-day BET and (2) the TM tape. Differences between the two state vectors are due to estimated systems errors. The BET state vector is based on Pulsed Integrating Pendulous Accelerometer (PIPA) and tracking data that have been corrected for estimated Inertial Measurement Unit (IMU) errors and tracking uncertainties.

The BET indicates that Apollo 10 achieved entry interface at 191 hours 48 minutes 52.16 seconds after liftoff. The entry state vector obtained from the BET is as follows:

Inertial Velocity	36,309.257 ft/sec
Inertial Flight Path Angle	-6.6165171 deg
Inertial Azimuth	71.928267 deg
Longitude	174.24393 deg East
Geodetic Latitude	23.651741 deg South
Geodetic Altitude	406,441.29 ft

The entry state vector recorded on the TM tape, corresponding to a time of 191 hours 48 minutes 52.16 seconds, was slightly different from the BET vector. It is:

Inertial Velocity	36,309.548 ft/sec
Inertial Flight Path Angle	-6.6198381 deg
Inertial Azimuth	71.9317 deg
Longitude	174.24384 deg East
Geodetic Latitude	23.653003 deg South
Geodetic Altitude	405,350.30 ft

The difference between state vectors were minute and did not have an appreciable effect on the entry trajectory.

3. CMC EVALUATION

The purpose of this section is to present an evaluation of the performance of the Apollo 10 entry GNCS system. A description of the guidance system's operation with respect to various trajectory parameters and terminal objectives is presented. Then, the CMC in-flight computations recorded on the TM tape are compared to values obtained from a simulation of the CMC utilizing the PIPA data recorded on the TM tape.

3.1 Description of the CMC Operation

The Apollo 10 atmospheric entry trajectory basically consisted of three phases: entry initialization (program 63), post 0.05g (program 64), and final phase (program 67). Programs 61 and 62 operated correctly and sequenced to program 63 at the proper time. The CMC remained in program 63 until the edge of the sensible atmosphere (0.05g) was reached. At this point atmospheric guidance began. Once the computed drag level, KA, was reached, the constant drag control logic was flown until the predicted velocity at the end of UPCONTROL (VL) was less than 18,000 ft/sec. The trajectory flown in final phase resulted in a computed touchdown at a geodetic latitude of 15.07 degrees south and a longitude of 164.65 degrees west, approximately 1.4 nautical miles from the planned touchdown point. The actual CMC sequencing is compared to the CMC simulation in Table I and the respective touchdown points are compared in Figure 1. The CMC simulation was obtained from the Apollo Reentry Simulation (ARS) program externally driven by the PIPA data.

3.1.1 Entry Initialization (Program 63).- The guidance system was initialized with the proper switches and control constants in program 63. At a geodetic altitude of 400,000 feet, the CMC indicated an inertial velocity of 36314.3 ft/sec and an inertial flight path angle of -6.56 degrees. The ground elapsed time from liftoff to entry interface was 191 hours 48 minutes 53 seconds. The entry point was located at a geodetic latitude of 23.616 degrees south and a longitude of 174.36 degrees east which resulted in a relative range of 1292.9 nautical miles and an inertial range of 1378.24 nautical miles. Onset of 0.05g occurred 28.73 seconds after entry at a geodetic altitude of 296,990.8 feet. The CMC then correctly calculated the reference drag level to initiate the constant drag logic, KA, the reference drag level for the constant drag logic, DO, and the command module's position in the entry corridor relative to the lift vector orientation (LVO) line. The values of KA and DO, based on the TM tape inertial velocity at 0.05g, were 1.468g's and 4.0272g's respectively, while the commanded bank angle was zero degrees.

3.1.2 Post 0.05g (Program 64).- The CMC then correctly sequenced to program 64 at 0.05g. The lift-up attitude commanded at the end of program 63 was maintained until the drag level became greater than 1.468g's 51 seconds after entry, at which time the guidance system began the constant drag portion of the trajectory.

The lift-to-drag ratio (L/D) control equation in the constant drag logic is driven by drag and altitude rate errors based on a computed reference trajectory. Initially the commanded bank angle was zero degrees (lift vector up) (Figure 2) due to the large negative altitude rate. The altitude rate became more positive than -700 ft/sec, 78 seconds after entry (Figure 3) and the guidance system began generating ranging predictions. The inertial range to the target at this time was 921 nautical miles (Figure 4). Due to the large energy level of the command module, an overshoot trajectory was predicted, hence the guidance system remained in the constant drag logic. The maximum load factor, 6.762g's, occurred 81 seconds after entry and the first minimum altitude (Figure 5), 181,736.8 feet, occurred 83 seconds after entry. When the load factor dropped below 5.44g's the guidance system properly commanded a bank angle of -180 degrees. The altitude increased to a relative maximum of 192,466 feet, 128 seconds after entry, while the load factor decreased to a relative minimum of 2.796g's, 129 seconds after entry.

The first roll command other than full lift-up occurred 87 seconds after entry and was 23 degrees. Four seconds later, the guidance system commanded a bank angle greater than 90 degrees but since the drag level was greater than 5.44g's, the roll command was limited to 90 degrees. Had the roll command not been limited to 90 degrees, the Digital Autopilot (DAP) would have commanded a longer period of jet on time, hence, a greater angular impulse, thereby increasing the possibility of flying to the reference drag level of 4.03g's. The large overshoot of the reference drag level was a result of the low average angular acceleration during the roll maneuver to the lift down attitude, as shown in Figure 6. It should be noted that the actual roll angular acceleration during this time was approximately 5.0 degrees per second squared, as expected from preflight data. However, the sequence of roll commands were such that the jets were turned off during part of the roll down maneuver and resulted in a low average angular acceleration. The Huntest phase of program 64 continued predicting overshoot trajectories until the predicted velocity at the end of UPCONTROL was less than 18,000 feet per second. This occurred 138 seconds after entry at which time the final phase logic (Program 67) was entered.

3.1.3 Final Phase (Program 67).- The guidance system sequenced to the final phase logic when the inertial velocity was 25033 feet per second and the altitude rate was -374 feet per second. The CM was in a lift vector down attitude and the inertial range to the target was 641 nautical miles. The first range prediction in final phase (refer to Figure 7) resulted in a predicted downrange undershoot error of 132 nautical miles. The predicted downrange error then increased rapidly to a maximum undershoot value of 187 nautical miles 147 seconds after entry. This was the result of the initial lift vector down attitude in P67. However, at EI + 165 seconds the first non-zero roll command was issued. At this time, the predicted downrange error was a 16.5 nautical mile undershoot, the crossrange error was predicted to be 4.5 nautical miles north of the target and the bank angle command was 15.41 degrees north. The overall trajectory flown in final phase was at an average bank angle of approximately 70 degrees and resulted in a touchdown at a geodetic latitude of 15.07 degrees south and a longitude of 164.65 degrees west. This trajectory culminated within 1.4 nautical miles of the target as shown in Figure 1.

Four bank angle reversals occurred during final phase. A bank angle reversal occurs whenever the crossrange deadband is exceeded. Crossrange deadband is computed by the guidance and is proportional to the spacecraft's lateral ranging capability at its current velocity. If the bank angle command is within ±15 degrees of full lift up or down, the deadband is halved to account for the smaller lateral force. The reversals occurred at 217 seconds, 339 seconds, 383 seconds, and 421 seconds after entry as indicated in Figure 8.

3.2 Computer Simulation

A computer simulation of the CMC operation during entry was made utilizing the PIPA data on the TM tape. The entry parameters obtained from the simulation were then compared to those recorded on the TM tape.

3.2.1 <u>Simulation</u> - The computer simulation of the CMC operation was made with the Apollo Reentry Simulation (ARS) program utilizing four-degree-of-freedom and the external drive option. The simulated CMC was initialized with the entry state vector obtained from the TM tape at a g.e.t. of 689,892 seconds. PIPA counts from the TM tape were used to drive the simulation.

3.2.2 <u>Comparison</u> - The results obtained from the PIPA drive simulation (simulated CMC) were compared to the CMC computations recorded on the TM tape and were in close agreement. In addition, the program sequencing obtained from the simulated CMC was identical to that of the actual CMC. The comparisons are shown in Figure 2 through 8 and in Tables I through III.

4. EVALUATION OF THE ENTRY OPERATIONS AND MONITORING PLAN

This section provides a chronological sequence of events of crew operations while monitoring entry. The data presented is obtained from the onboard telemetry tape and indicates what the crew observed in real time via the DSKY displays and how they responded in the process of monitoring entry. Table V presents the Apollo 10 sequence of events in addition to PAD data necessary to monitor the onboard computer.

4.1 Entry Monitoring Prior to Entry Interface

Program 61 was initiated 19 minutes and 10 seconds prior to EI. At this time the command and service module (CSM) was maintained at an attitude of 269 degrees pitch, 317 degrees yaw, and 4 degrees roll. The CSM was maintained at approximately this attitude until separation (refer to Figure 9). The first DSKY display appeared at EI - 18 minutes and 56 seconds. The target latitude and longitude and lift vector orientation (LVO) were displayed. The target latitude was 15.07 degrees south and longitude was 164.67 degrees west; the actual splashdown coordinates were 15.07 south and 164.65 west. The LVO was displayed in the up orientation. At EI - 18 minutes, 50 seconds, the DSKY predicted values of GMAX = 6.56g's, velocity at EI = 36,311 ft/sec and flight path angle at EI = -6.48 degrees were displayed. These values compared very favorably to the actual (BET) conditions of GMAX = 6.76g's, Velocity (EI) = 36,314 ft/sec and flight path angle (EI) = -6.54. At EI - 18 minutes, 26 seconds, the final DSKY display of P61 was obtained. The predicted inertial range to the target at 0.05g = 1221 nautical miles, predicted time of 0.05g = EI + 28 seconds. The actual values of inertial range to target at 0.05g = 1218 and inertial velocity at 0.05g = 36394. These values compared favorably. The time of 0.05g occurred as predicted.

Program 62 was entered at EI - 18 minutes 14 seconds. The request for separation appeared immediately; consequently, the IMU was neither reversed nor unsatisfactory. At EI - 17 minutes, the pitch gimbal angle check was performed. The actual pitch gimbal angle was two degrees less than the Pad value of 268; this is well within the allowable five degree tolerance.

CM/SM separation occurred at EI - 15 minutes, 26 seconds. The command pilot waited 84 seconds after separation to insure adequate separation distance. Fourteen minutes prior to entry the DSKY display of target coordinates appeared with the lift vector orientation for entry. The values were the same as in P61. At EI - 12 minutes and 38 seconds, the DSKY display of desired gimbal angles appeared: Roll = 359.5 degrees, Pitch = 179.9 degrees and Yaw = 359.6 degrees. The DSKY display of desired gimbal angles was displayed until EI - 11 minutes, 52 seconds; at this time, program 63 automatically sequenced in. The DSKY display of load factor = 0.0, inertial velocity = 30,738 ft/sec and range to go =

4562 nautical miles appeared. The load factor remained constant until after entry interface, the inertial velocity increased to 36397 ft/sec and then decreased from this point, and the range to go naturally decreased throughout entry.

Figure 9 indicates that the crew chose the option of maintaining the 0.05g attitude after separation. At EI - 6 minutes, 12 seconds to approximately EI - 3 minutes, 52 seconds the pitch gimbal angle was maintained at approximately 156 degrees. The pitch gimbal angle varied between 155 to 152 degrees from EI - 3 minutes, 52 seconds to entry interface.

4.2 Entry Operations and Monitoring After Entry Interface

The crew maintained manual control of the CM for a few seconds after the time of entry interface. The pitch error needle was within 15 degrees of the desired attitude from EI - 9 minutes and 42 seconds (refer to Figure 9). The crew switched to DAP control at approximately EI + 16 seconds.

The occurance of 0.05g was within the 2 second computer interval of the predicted time. Program 64 and the entry monitor system sequenced in immediately. At EI + 30 seconds, the first P64 DSKY display of bank angle command = 0.0 degree, inertial velocity = 36,396 ft/sec and altitude rate = -3271 ft/sec was available. The Huntest phase of the entry guidance was entered at EI + 1 minute and 18 seconds. Ten seconds later the guidance system issued the first non-zero bank angle command. Figure 10 indicates that the entry trajectory flown by the guidance was very near nominal. The solid line indicates the telemetry data had no slope tangent to the skip-out lines; however, observations of the actual EMS scroll pattern trace (dashed line on Figure 10) indicates the possibility of a tangency existing at approximately 29,300 ft/sec. At this point in the trajectory, the guidance bank angle command is monitored to determine if it is commanding a lift down orientation, thereby insuring that the guidance system is functioning correctly. The bank angle command is lift vector down (180 degrees) thereby satisfying the monitoring plan.

The entry pad value of the time of V_{CIRC} was EI + 2 minutes, 8 seconds. At this time the actual velocity of the vehicle is 25,896 ft/sec. The actual time of V_{CIRC} occurred at EI + 2 minutes, 12.6 seconds.

The program sequencing from P64 to P67 was as predicted on the entry pad. Program 67 was automatically entered 5 seconds after the actual time of V_{CIRC}. The first DSKY display during P67 indicated an undershoot of 132 nautical miles; however, within 24 seconds this deficit was corrected. With the most critical portion of entry successfully negotiated, ranging to the target and avoiding high g loads is the primary concern. At EI + 7 minutes and 18 seconds, the DSKY display of RTOGO = 1.3 (undershoot), present latitude = 15.09 degrees south and present longitude = 164.69 degrees west indicates that the target was achieved by the guidance system. The drogue chutes were deployed at EI + 8 minutes and 18 seconds and the main chutes were deployed approximately 50 seconds later.

5. TRAJECTORY RECONSTRUCTION

The reconstructed entry trajectory is presented in this section and the resulting trajectory is compared to the 21-day BET. The entry parameters that were varied to match the BET were the CM aerodynamics and the atmospheric model. The CM weight used was the pre-entry estimated value of 12121.5 pounds and was held constant in the analysis.

The Apollo 10 entry trajectory was reconstructed in two ways, both using external drives. The first used the gimbal angle data from the TM tape at 2-second intervals. The data was converted to body attitudes without exercising the CMC logic. The second type of simulation used the PIPA data from the TM tape as inputs to the CMC. The simulated CMC then calculated the bank angle commands from the PIPA data and supplied them to the digital autopilot.

5.1 Entry Parameters

The selection of the CM aerodynamics and atmospheric model was based on the reconstruction of an entry trajectory that had the best overall comparison to the following trajectory parameters: 1) first and second maximum load factor, 2) first minimum load factor, 3) first maximum and minimum altitude, 4) touchdown point, and 5) time of drogue deployment. The aerodynamic characteristics of the CM used in the postflight reconstruction were obtained from the TM tape. Figure 11 presents the time history of L/D's recorded on the TM tape. Deviations about the TM value of the hypersonic L/D 's were between 0.308 and 0.315. The aerodynamic coefficients used in the trajectory simulations were obtained as a function of Mach number from the Block II vehicle data (Reference 2). The PIPA L/D was constant until approximately 140 seconds after the time of 0.05g. Calculations, based on the TM inertial velocity and altitude, indicated that the Mach number at this time was approximately 21. The final reconstructed trajectory required an L/D of 0.312 and is shown in Figure 12. Also shown in the figure is the TM L/D as well as the preentry estimated value. The atmospheric model selected for the reconstruction was 30 degrees north (January)(Reference 3).

5.2 Method Of Trajectory Reconstruction

The values of L/D recorded on the TM tape indicated that the hypersonic L/D for Apollo 10 was between 0.308 and 0.315. Various hypersonic L/D ratios were run with several atmospheres to determine the L/D and atmosphere which best simulate the actual Apollo 10 load factors through maximum and minimum g.

With the best estimate of L/D and atmosphere, a PIPA run is made. This run verifies that the CMC functioned properly. The PIPA run indicated that the bank angle commands issued were exactly the same as the actual bank angle commands except for the last few seconds of the trajectory.

Although the PIPA drive run indicated that the guidance system operated very well, it also indicated that there was a discrepancy with the attitude the vehicle attained. The PIPA run was approximately 8 degrees less than the attitude achieved by the actual vehicle and recorded on TM tape. This indicated that the vehicle had a possible roll moment. Refer to Figure 13 and note the vehicle roll attitude beginning to change as it reaches the sensible atmosphere.

With a roll attitude error, all PIPA driven trajectories will have substantial target misses. For the Apollo 10 conditions, an L/D of 0.312 and a 30 degree N latitude atmosphere, the PIPA run missed the target by 133 N. Mi. Obviously, the trajectory reconstruction must be handled in a fashion that is free from the attitude error. The gimbal angle drive lends itself nicely to this situation. A comparison of the gimbal angle drive (G.A.D.) and the telemetry tape load factors is presented below:

MAX G (TM)	MAX G (G.A.D.)	MIN G (TM)	MIN G (G.A.D.)	2nd MAX (TM)	2nd MAX (G.A.D.)
6.76	6.77	2.80	2.76	4.60	4.47

The agreement between the load factors of the TM and gimbal angle drive was excellent. The net result of this agreement is that the vehicle lands within 7 miles of the target. The load factors presented above are in complete agreement with the BET. The values for the BET are as follows:

(1) MAX G = 6.78, (2) MIN G = 2.79 and (3) second MAX G = 4.54

These results indicate that there was an excellent agreement between the TM, GAD, and BET trajectories. Figures 14-16 present comparisons of altitude, velocity and load factor histories.

6. VEHICLE PERFORMANCE

This section presents a summary of the performance of Apollo 10 CM systems related to atmospheric entry. The inertial measuring unit (IMU) errors were not available. These errors, in the past, have been relatively insignificant and have produced negligable touchdown dispersions. The effect of these errors can be seen in Table IV, for the Apollo 10 entry phase. The EMS and the reaction control system (RCS) were evaluated.

6.1 The Entry Monitor System

The EMS performed very well for Apollo 10. The scroll pattern trace was much smoother than for the previous missions. The actual Apollo 10 EMS scroll trace is presented as the dashed line in Figure 10. The solid line represents the telemetry data. The results of the figure indicate a close agreement between the actual scroll pattern trace and the telemetry data plotted on the scroll pattern. The actual scroll pattern trace indicated that a tangency occurred at approximately 29,300 ft/sec; however, the guidance system was issuing proper roll commands indicating that no violation occurred. The EMS was a very adequate monitoring device.

6.2 RCS Propellant Consumption

The actual Apollo 10 propellant consumption was 33.0 lbs. This value of fuel consumption was not in good agreement with the internally driven 6-D simulation (23.6 lbs) nor the roll command driven 6-D simulation (24.3 lbs). The models of fuel consumption for the 6-D simulations seem to have a consistent error of no fuel consumption in the pitch control axis. The simulations of propellant consumption for the negative roll jets was in error by approximately 5 pounds. This difference is not a significant error since there are over 200 pounds of fuel available for the entry phase. The fuel consumption for each of the control axes is shown below:

CONTROL AXIS	INTERNALLY DRIVEN 6-D SIMULATION	ROLL COMMAND DRIVEN 6-D SIMULATION	ACTUAL APOLLO 10
+Roll	8.99	9.38	8.88
-Roll	10.21	10.06	14.98
TOTAL	19.20	19.44	23.86
+Pitch	0.0	0.0	1.0
-Pitch	0.03	0.14	3.9
TOTAL	0.03	0.14	4.9
+Yaw	1.15	2.47	2.26
-Yaw	3.19	2.24	1.98
TOTAL	4.34	4.71	4.24

Most of the pitch and yaw axis control activity occurred during the final two minutes before drogue deployment. The usage is presented below:

Control Axis	Propellant consumed during the two minutes prior to drogue deployment - based on simulated data (POUNDS)
+Pitch	0.0
-Pitch	0.14
TOTAL	0.14
+Yaw	2.00
-Yaw	1.76
TOTAL	3.76

The increased activity of the pitch and yaw jets indicates that a degree of dynamic instability exists at low Mach numbers.

Table I. Comparison of the Actual CMC and Simulated CMC Guidance

Guidance Phase		Time from Lift-off (hr:min:sec)	Inertial Velocity (ft/sec)	Inertial Range to Target (NM)	Altitude Rate (ft/sec)
Entry Interface	Actual CMC	191:48:53.4	36314.3	1378.24	-4147.20
	Simulated CMC	191:48:53.2	36313.9	1384.94	-4154.56
0.05g (P63-P64)	Actual CMC	191:49:20.8	36394.1	1213.88	-3314.27
	Simulated CMC	191:49:20.9	36394.4	1213.31	-3311.14
Begin Guidance (Huntest)	Actual CMC	191:50:10.2	32824.0	921.36	-640.70
	Simulated CMC	191:50:10.2	32823.8	921.40	-640.70
Final Phase (P67)	Actual CMC	191:51:10.2	25032.7	641.21	-374.17
	Simulated CMC	191:51:10.2	25032.6	641.25	-373.15
Guidance Termination	Actual CMC	191:56:10.2	2306.7	1.40	-667.35
	Simulated CMC	191:56:10.2	2305.2	1.33	-667.14

Table II. Comparisons of Bank Angle Commands From The Actual CMC and CMC Simulations

TIME FROM ENTRY INTERFACE	ACTUAL CMC BANK ANGLE COMMAND	CMC SIMULATION BANK ANGLE COMMAND
0	0.0	0.0
88	22.9	22.9
90	82.1	82.1
92	90.0	90.0
94	90.0	90.0
96	180.0	180.0
138	0.0	0.0
166	15.4	15.9
170	41.7	41.7
174	49.5	49.6
180	35.3	35.8
182	32.4	32.5
190	42.4	42.5
200	51.9	52.0
210	54.2	54.4
216	54.6	54.9
218	-55.3	-55.3
230	-68.3	-68.3
240	-74.2	-74.5
250	-79.3	-79.3
260	-81.1	-81.2
270	-82.3	-82.5
280	-81.9	-82.2
290	-82.3	-82.4
300	-77.2	-77.5
310	-73.5	-73.5
320	-70.4	-70.5
322	-43.7	-44.1
330	-32.1	-32.6
338	-58.8	-58.3
340	62.8	62.8
342	63.0	62.9
350	91.9	91.5
352	94.0	94.0
360	78.5	79.1
370	72.5	73.7
380	64.1	65.0
382	57.0	59.0
384	-48.9	-52.2
390	-65.5	-67.4
396	-81.1	-84.6
400	-84.7	-86.4
410	-83.3	-84.1
418	-86.0	-85.2
420	-80.0	83.7
428	93.5	106.3
430	102.6	103.7
432	103.4	108.7
434	105.0	102.6
436	88.8	101.3

Table III. Comparison of the Actual CMC State Vector to the Simulated CMC State Vector

ELAPSED TIME (hr:min:sec)	TIME FROM ENTRY INTERFACE (sec)	ACTUAL CMC STATE VECTOR (ft) and (ft/sec)	SIMULATED CMC STATE VECTOR (ft) and (ft/sec)	EVENT
191:48:52.2	-1.2	$X = 11976174.0$	$X = 11976123.0$	The approximate time of entry interface
		$Y = -15451660.0$	$Y = -15451640.0$	
		$Z = -8506213.9$	$Z = -8506260.4$	
		$\dot{X} = 27484.486$	$\dot{X} = 27484.367$	
		$\dot{Y} = 20511.779$	$\dot{Y} = 20511.661$	
		$\dot{Z} = 11927.622$	$\dot{Z} = 11927.475$	
191:49:22.8	28.8	$X = 12792638.0$	$X = 12792572.0$	P64 is entered
		$Y = -14826332.0$	$Y = -14826306.0$	
		$Z = -8142880.6$	$Z = -8142928.9$	
		$\dot{X} = 26934.425$	$\dot{X} = 26934.320$	
		$\dot{Y} = 21169.436$	$\dot{Y} = 21169.314$	
		$\dot{Z} = 12289.928$	$\dot{Z} = 12289.779$	
191:50:14.8	80.8	$X = 14134875.0$	$X = 14134804.0$	Time of maximum load factor
		$Y = -13745026.0$	$Y = -13745011.0$	
		$Z = -7514842.5$	$Z = -7514890.2$	
		$\dot{X} = 23546.782$	$\dot{X} = 23546.717$	
		$\dot{Y} = 18698.449$	$\dot{Y} = 18698.328$	
		$\dot{Z} = 10934.518$	$\dot{Z} = 10934.373$	
191:51:02.8	128.8	$X = 15121496.0$	$X = 15121428.0$	Time of minimum load factor
		$Y = -12944619.0$	$Y = -12944609.0$	
		$Z = -7036876.6$	$Z = -7036928.5$	
		$\dot{X} = 17830.480$	$\dot{X} = 17830.445$	
		$\dot{Y} = 15931.690$	$\dot{Y} = 15931.573$	
		$\dot{Z} = 9486.6537$	$\dot{Z} = 9486.5145$	

Table III. Comparison of the Actual CMC State Vector to the Simulated CMC State Vector (Continued)

ELAPSED TIME (hr:min:sec)	TIME FROM ENTRY INTERFACE (sec)	ACTUAL CMC STATE VECTOR (ft) and (ft/sec)	SIMULATED CMC STATE VECTOR (ft) and (ft/sec)	EVENT
191:51:10.8	136.8	$X = 15260899.0$ $Y = -12817684.0$ $Z = -6961509.1$ $\dot{X} = 17017.461$ $\dot{Y} = 15798.499$ $\dot{Z} = 9351.4906$	$X = 15260832.0$ $Y = -12817675.0$ $Z = -6961568.8$ $\dot{X} = 17017.430$ $\dot{Y} = 15798.382$ $\dot{Z} = 9351.3521$	P67 is entered
191:56:10.8	436.8	$X = 17671515.0$ $Y = -9926384.4$ $Z = -5429179.7$ $\dot{X} = 550.32405$ $\dot{Y} = 2216.8510$ $\dot{Z} = 317.32370$	$X = 17671481.0$ $Y = -9926440.0$ $Z = -5429290.2$ $\dot{X} = 550.0382$ $\dot{Y} = 2216.1335$ $\dot{Z} = 317.20209$	Guidance termination

Table IV. Comparison Of The Actual CMC State Vectors To The BET State Vectors

Elapsed Time (hr:min:sec)	Time From Entry Interface (Sec)	Actual CMC State Vector (Ft) & (Ft/Sec)	BET State Vector (Ft) & (Ft/Sec)	Event
191:48:52.2	-1.2	$X = 11976174.0$ $Y = -15451660.0$ $Z = -8506213.9$ $\dot{X} = 27484.486$ $\dot{Y} = 20511.779$ $\dot{Z} = 11927.622$	$X = 11976744.0$ $Y = -15452783.0$ $Z = -8506040.2$ $\dot{X} = 27485.496$ $\dot{Y} = 20510.112$ $\dot{Z} = 11926.649$	The Approximate Time of Entry Interface
191:49:22.8	28.8	$X = 12792638.0$ $Y = -14826332.0$ $Z = -8142880.6$ $\dot{X} = 26934.425$ $\dot{Y} = 21169.436$ $\dot{Z} = 12289.928$	$X = 12793225.0$ $Y = -14827496.0$ $Z = -8142734.1$ $\dot{X} = 26935.497$ $\dot{Y} = 21167.711$ $\dot{Z} = 12288.887$	P64 is Entered
191:50:14.8	80.8	$X = 14134875.0$ $Y = -13745026.0$ $Z = -7514842.5$ $\dot{X} = 23546.782$ $\dot{Y} = 18698.449$ $\dot{Z} = 10934.518$	$X = 14135504.0$ $Y = -13746279.0$ $Z = -7514740.7$ $\dot{X} = 23546.982$ $\dot{Y} = 18697.13$ $\dot{Z} = 10933.632$	Time of Maximum Load Factor
191:51:02.8	128.8	$X = 15121496.0$ $Y = -12944619.0$ $Z = -7036876.6$ $\dot{X} = 17830.480$ $\dot{Y} = 15931.690$ $\dot{Z} = 9486.6537$	$X = 15122107.0$ $Y = -12945909.0$ $Z = -7036802.6$ $\dot{X} = 17829.781$ $\dot{Y} = 15931.302$ $\dot{Z} = 9486.2228$	Time of Minimum Load Factor

Table IV. Comparison Of The Actual CMC State Vectors To The BET State Vectors (Cont'd)

Elapsed Time (hr:min:sec)	Time From Entry Interface (Sec)	Actual CMC State Vector (Ft) & (Ft/Sec)	BET State Vector (Ft) & (Ft/Sec)	Event
191:51:10.8	136.8	X = 15260899.0 Y =-12817684.0 Z = -6961509.1 $\dot{X}$ = 17017.461 $\dot{Y}$ = 15798.499 $\dot{Z}$ = 9351.4906	X = 15261505.0 Y =-12818976.0 Z = -6961444.8 $\dot{X}$ = 17016.698 $\dot{Y}$ = 15798.236 $\dot{Z}$ = 9351.1196	P67 is Entered
191:56:10.8	436.8	X = 17671515.0 Y = -9926384.4 Z = -5429179.7 $\dot{X}$ = 550.32405 $\dot{Y}$ = 2216.8510 $\dot{Z}$ = 317.32370	X = 17671265.0 Y = -9927462.5 Z = -5429118.4 $\dot{X}$ = 545.00372 $\dot{Y}$ = 2218.4171 $\dot{Z}$ = 317.57327	Guidance Termination

Table V. The Chronological Sequence of Events of the Apollo 10 Entry and Available Pad Data Necessary to Monitoring Entry

APOLLO 10 MISSION EVENT TIME	APOLLO 10 EVENT	REAL TIME DATA PROVIDED TO CREW	COMMENTS
EI - 19 min 10 sec	P61 was initiated	Initiated P61 at EI - 19 min	The command and service module was held at an attitude of Pitch = 269 deg; Yaw = 317 deg; and Roll = 4 deg
EI - 18 min 56 sec	V06 - N61 DSKY DISPLAY Target Latitude = 15.07 deg, Target Longitude = -164.67 deg, Lift Vector Up	Target Latitude = -15.07 deg Target Longitude = -164.67 deg Lift Vector Up	
EI - 18 min 50 sec	V06 - N60 DSKY DISPLAY pred. GMAX = 6.56, pred. velocity (EI) = 36311 ft/sec, pred. flight path (EI) = -6.48	Pred. GMAX = 6.8 Pred. Velocity (EI) = 36315 ft/sec Pred. Flight Path = -6.54 deg	
EI - 18 min 26 sec	V06 - N63 DSKY DISPLAY pred. RTOGO (0.05g) = 1220.7 n mi Pred. Velocity (0.05g) = 36387 ft/sec; Pred. Time to 0.05g = EI + 28 sec	Pred. RTOGO (0.05g) = 1206.1 n mi Pred. Velocity (0.05g) = 36395 ft/sec Pred. Time to 0.05g = EI + 27 sec	
EI - 18 min 14 sec	P62 is entered	Initiate P62 at EI - 18 min	V25-N50 is flashing Requesting separation
* EI - 17 min	Pitch Gimbal Angle (PGA) Check is performed PGA = 265.9 deg	PAD PGA = 268 deg	The actual value of the PGA is sufficiently close to the PAD valve to successfully pass the monitoring plan test.

* The difference between the pad and actual PGA implies that the horizon was not on the 31.7 degree window mark at the time of the check.

Table V. The Chronological Sequence of Events of the Apollo 10 Entry and Available Pad Data Necessary to Monitoring Entry (Continued)

APOLLO 10 MISSION EVENT TIME	APOLLO 10 EVENT	REAL TIME DATA PROVIDED TO CREW	COMMENTS
EI - 15 min 26 sec	CM/SM separation occurred	CM/SM separation at EI - 15 min	
EI - 15 min 2 sec	Separation maneuver completed		The command pilot waited 84 seconds to provide adequate separation distance
EI - 14 min 0 sec	V06 - N61 DSKY DISPLAY The same values as for EI - 18 min 56 sec		Last chance to update target
EI - 12 min 38 sec	V06 - N22 DSKY DISPLAY Roll Gimbal Angle = 359.5 deg Pitch Gimbal Angle = 179.9 deg Yaw Gimbal Angle = 359.6 deg		
EI - 11 min 52 sec	P63 automatically sequenced in		
EI - 11 min 48 sec	V06 - N64 DSKY DIAPLAY Load factor = 0.0 Inertial velocity = 30,738 ft/sec RTOGO = 4562 n mi		
EI - 15 min 2 sec TO EI	Crew maintained 0.05g attitude	Crew provided two options: 1) Maintain 0.05g attitude 2) Track horizon on 31.7 degree mark on window	Pitch error needle will indicate proper functioning of G&N prior to entry

Table V. The Chronological Sequence of Events of the Apollo Entry and Available Pad Data Necessary to Monitoring Entry (Continued)

APOLLO 10 MISSION EVENT TIME	APOLLO 10 EVENT	REAL TIME DATA PROVIDED TO CREW	COMMENTS
EI - 3 min 52 sec to EI	Pitch Gimbal Angle varied between 155 and 152 deg	Pitch Gimbal Angle at 0.05g is 153 deg	
EI	Load factor = 0.0g Inertial velocity = 36310 ft/sec RTOGO = 1387.4 n mi	Inertial velocity = 36315 ft/sec	
EI + 0 min 28 sec	Load factor = 0.043g Inertial velocity = 36393 ft/sec RTOGO = 1218.9 n mi	Load factor = 0.05g Inertial velocity = 36395 ft/sec RTOGO = 1206.1 n mi	
EI + 0 min 30 sec	P64 sequenced in V06 - N68 DSKY DISPLAY Bank Angle Command = 0.0 deg Inertial velocity = 36396 ft/sec Altitude Rate = -3271 ft/sec	Bank Angle Command = 0.0 deg Inertial Velocity = 36395 ft/sec	
EI + 1 min 18 sec	Huntest phase entered RDOT = -641 ft/sec		
EI + 1 min 28 sec	First non-zero bank command Inertial velocity 30762 ft/sec RDOT = 171 ft/sec Bank Angle Command = 22.94 deg		
EI + 1 min 38 sec	Maximum positive RDOT = 681 ft/sec achieved		

Table V. The Chronological Sequence of Events of the Apollo 10 Entry and Available Pad Data Necessary to Monitoring Entry (Continued)

APOLLO 10 MISSION EVENT TIME	APOLLO 10 EVENT	REAL TIME DATA PROVIDED TO CREW	COMMENTS
EI + 2 min 12.6 sec	Actual time of VCIRC	PAD value of the time of VCIRC EI + 2 min 8 sec	The inertial velocity at EI + 2 min 8 sec 25896 instead of 25500 ft/sec
EI + 2 min 18 sec	Program 67 automatically sequence in V06 - N66 DSKY DISPLAY; Bank angle command = 0.0 Crossrange error = 11.0 n mi Downrange error = -132.4 n mi		The target is south of the present flight plane and the predicted downrange is short of the target
EI + 2 min 28 sec	Max downrange error of -186.9 n mi short of target. Crossrange error is 3.74 n mi north of target		
EI + 2 min 46 sec	Time of the first non-zero roll command in final phase Bank Angle Command = 15.41 deg Downrange error = -16.5 n mi Crossrange error = 4.5 n mi north of the target		
EI + 7 min 18 sec	V16-N67 DSKY DISPLAY RTOGO = -1.3 n mi Present Latitude = -15.09 deg Present Longitude = -164.69 deg		
EI + 8 min 18 sec	Drogues deploy	PAD value of Drogue Deploy was EI + 8 min 16 sec	

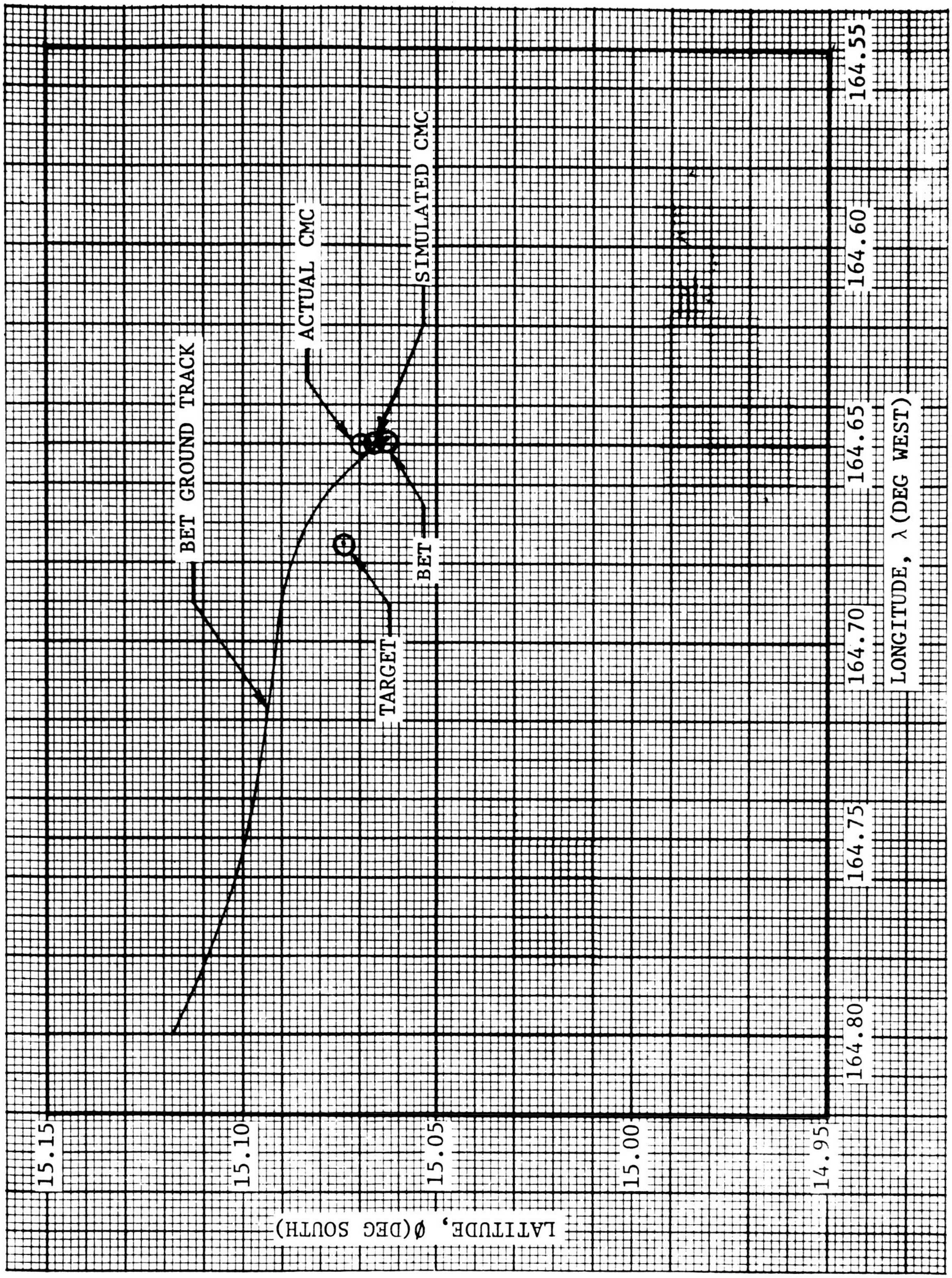

Figure 1. Touchdown and Target Locations

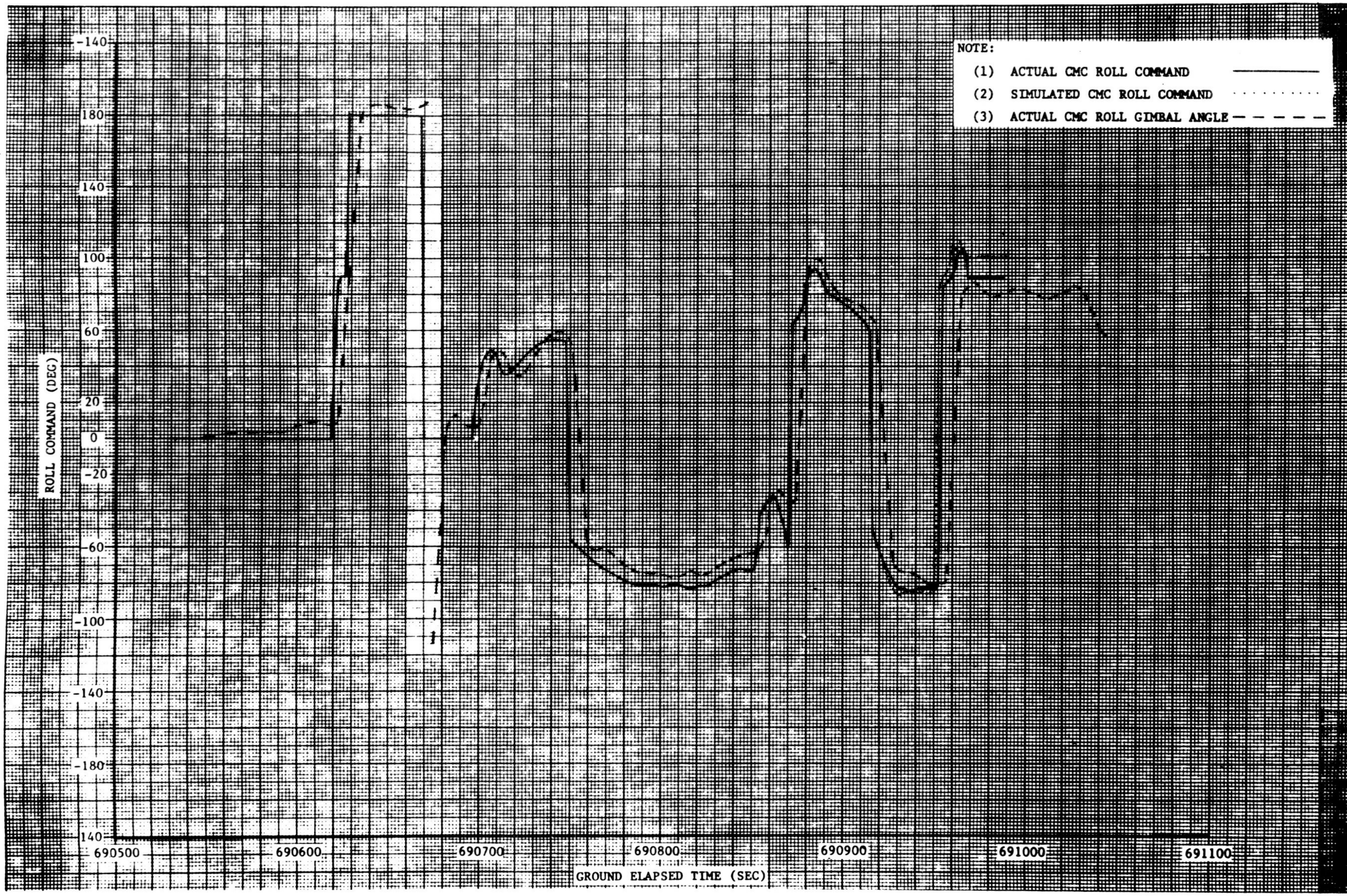

Figure 2. A Comparison of the Actual and Simulated CMC Roll Command in Conjunction with the Actual CMC Roll Gimbal Angle

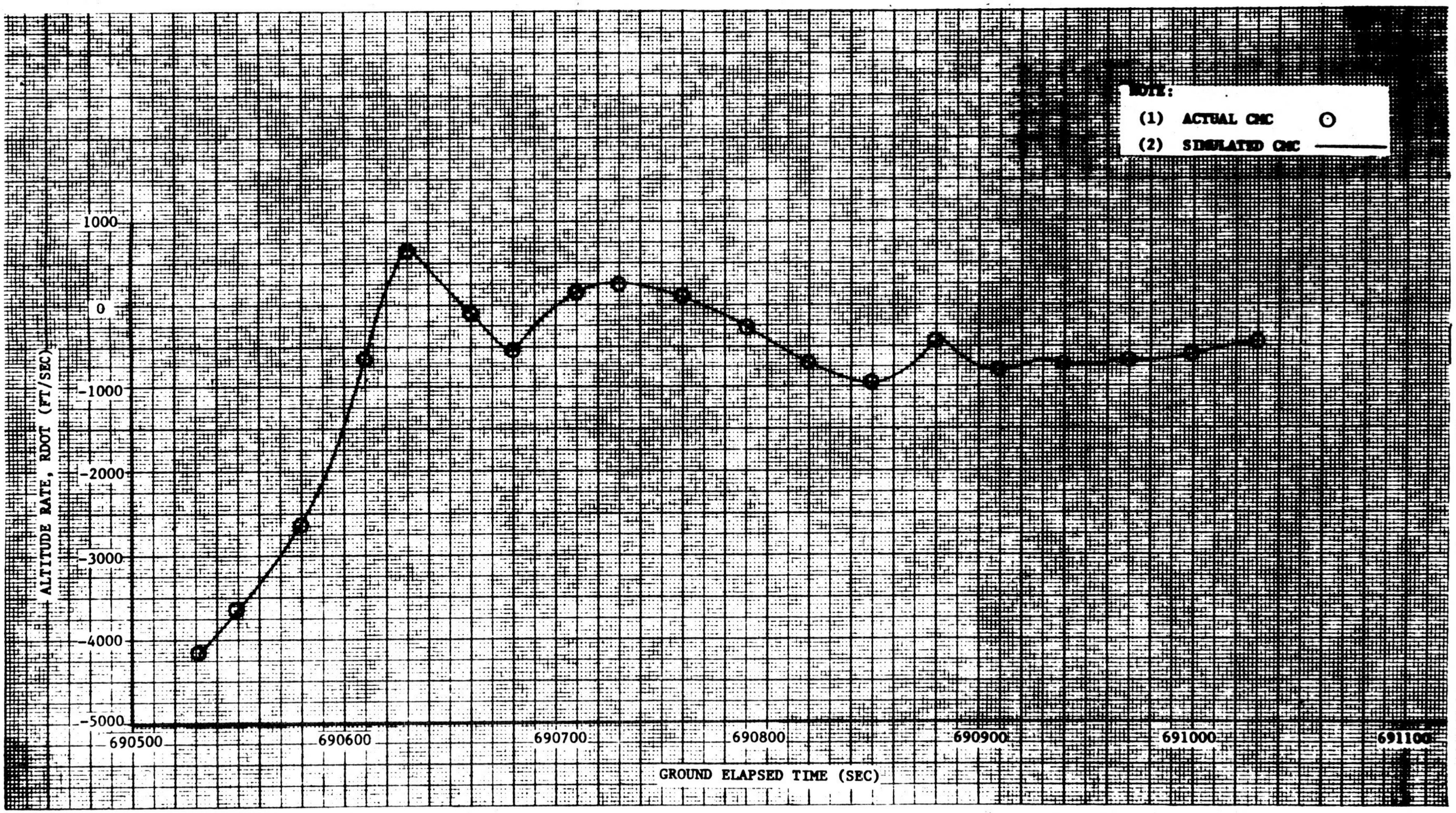

Figure 3. Comparison of the Altitude Rate History Between the Actual and Simulated CMC

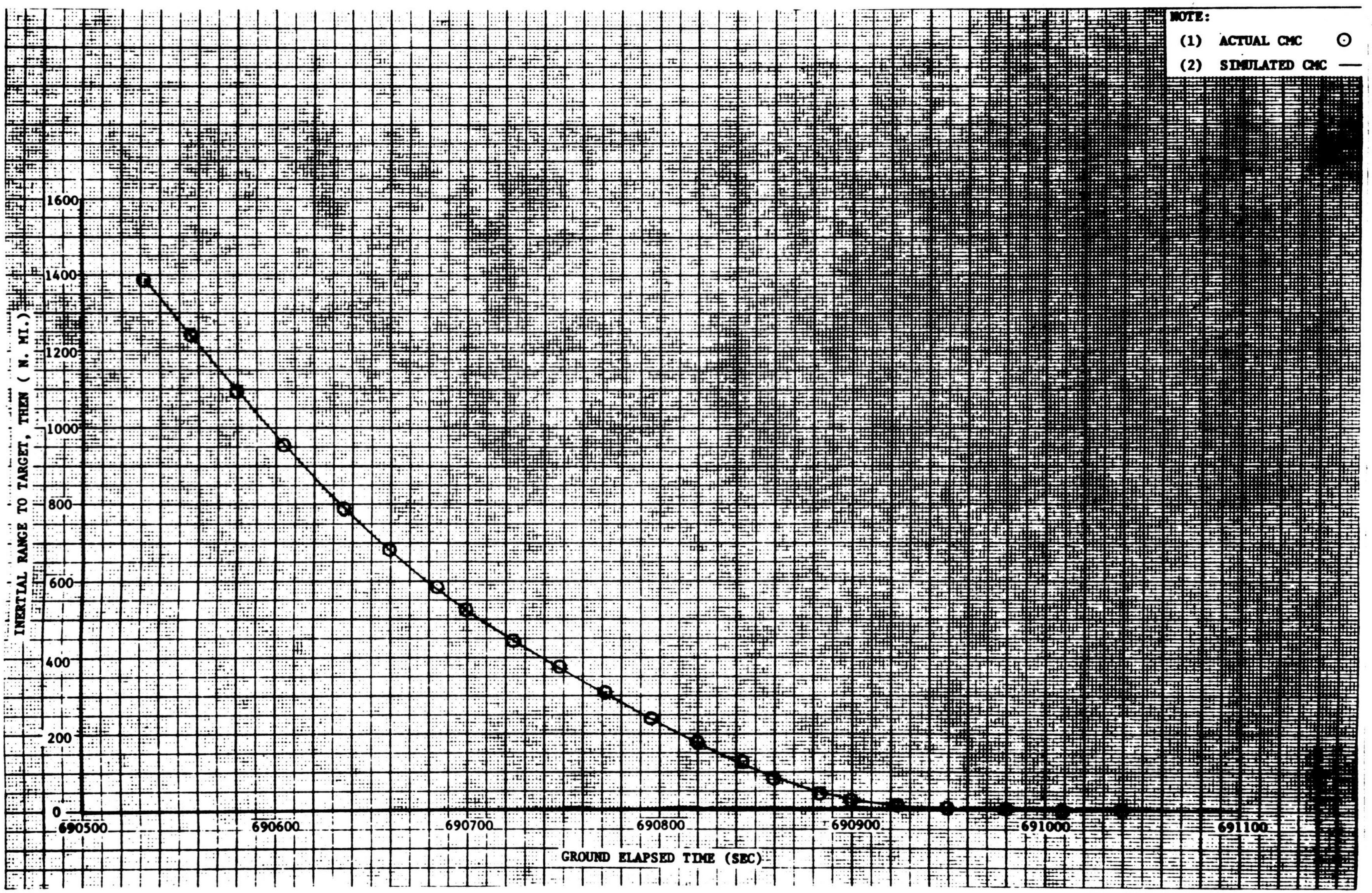

Figure 4. Comparison of the Actual CMC Inertial Range Predictions to the Simulated CMC

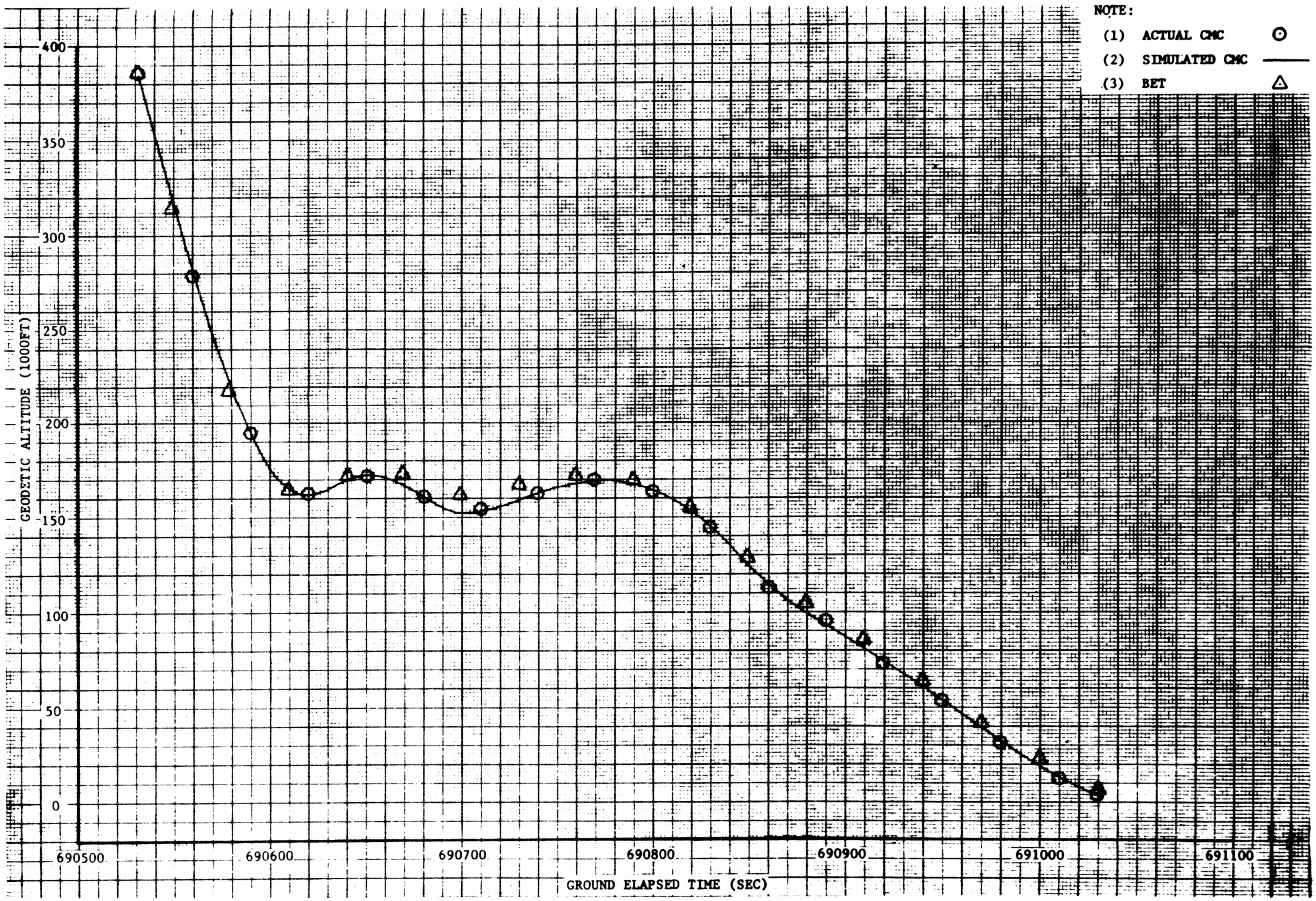

Figure 5. A Comparison of the Geodetic Altitudes Between the Actual CMC, the Simulated CMC and the BET

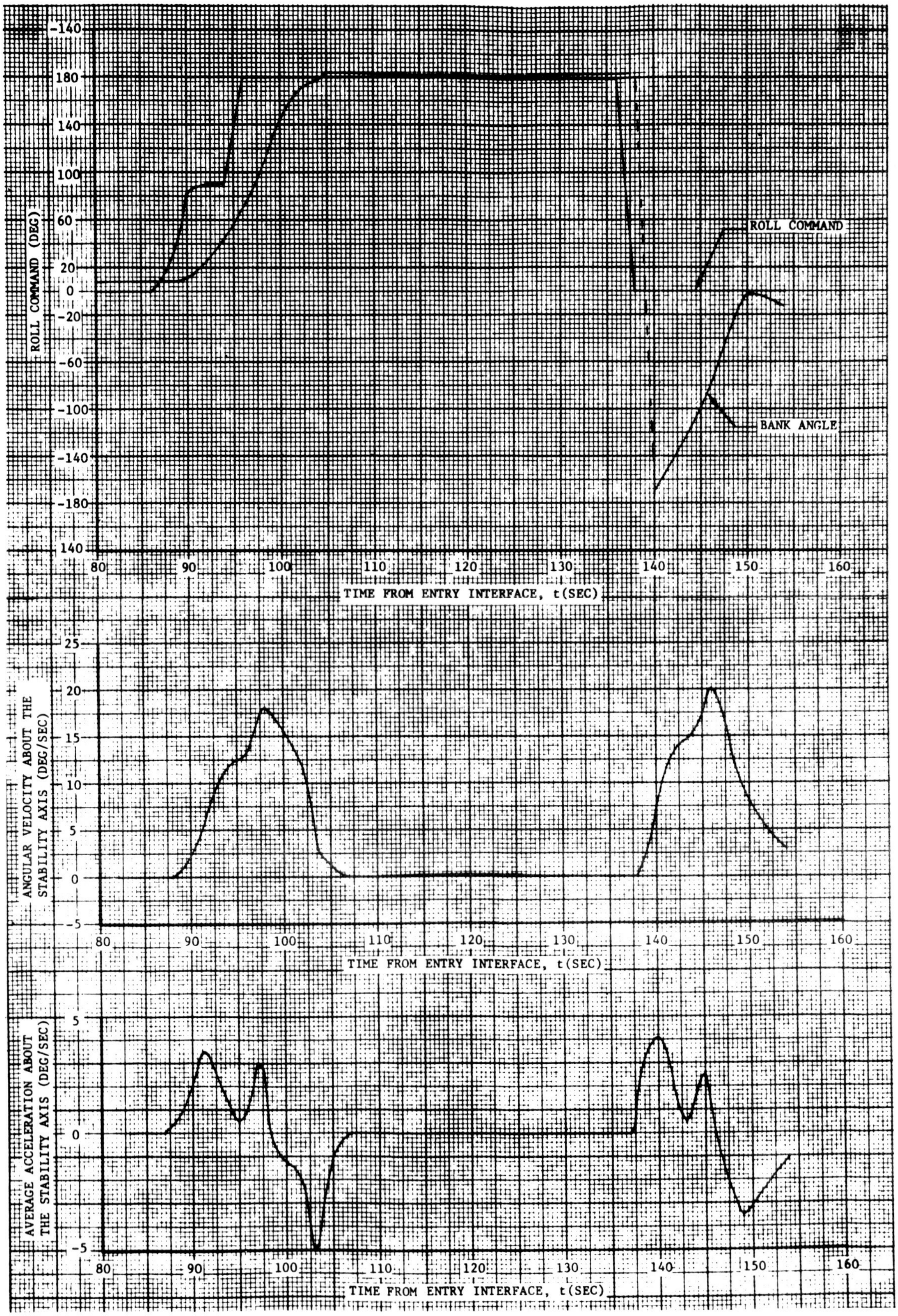

Figure 6. Actual Command Module Performance Between First Peak G and First Minimum G

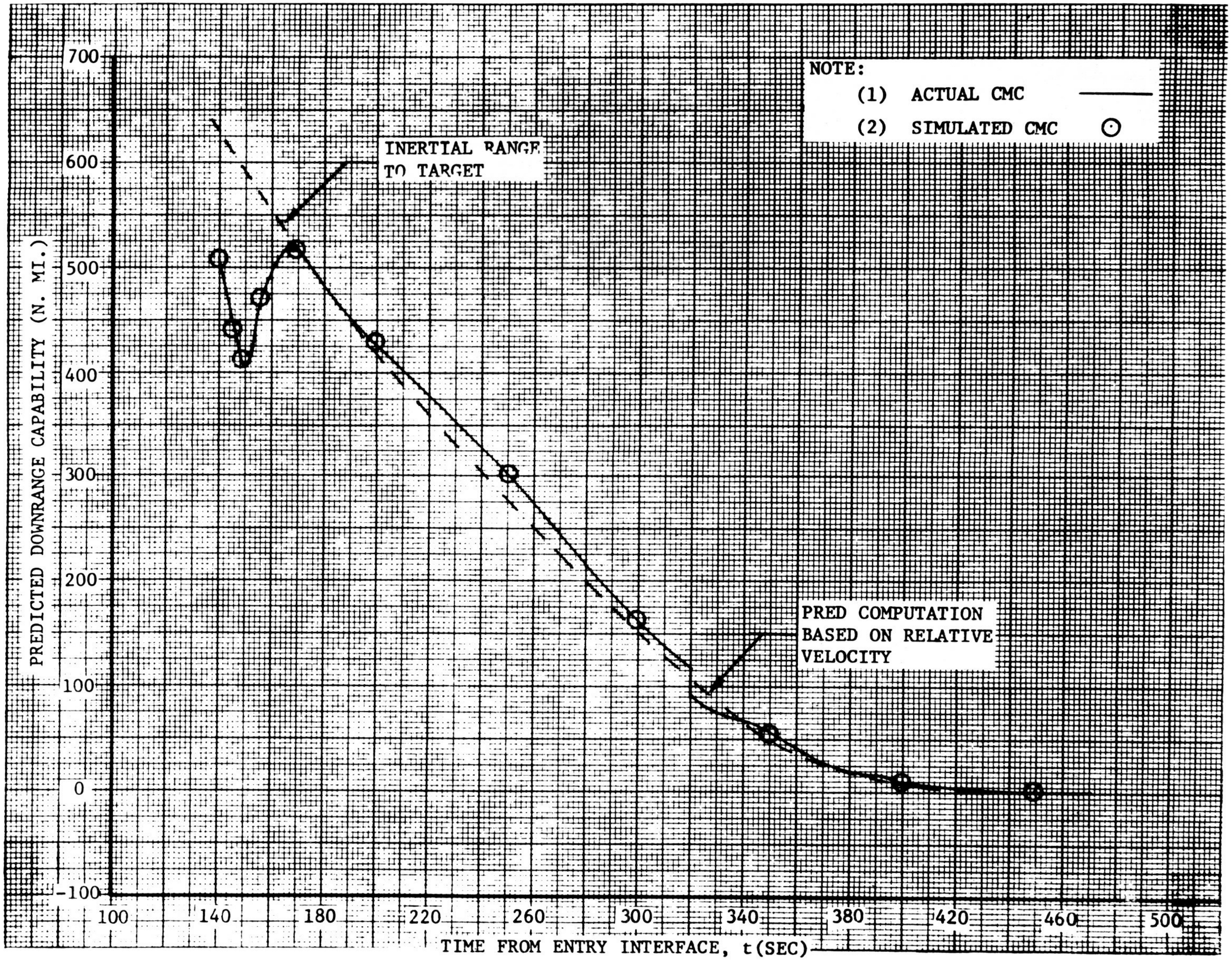

Figure 7. Comparison of the Downrange Capability Predicted by the Actual CMC to the Simulated CMC

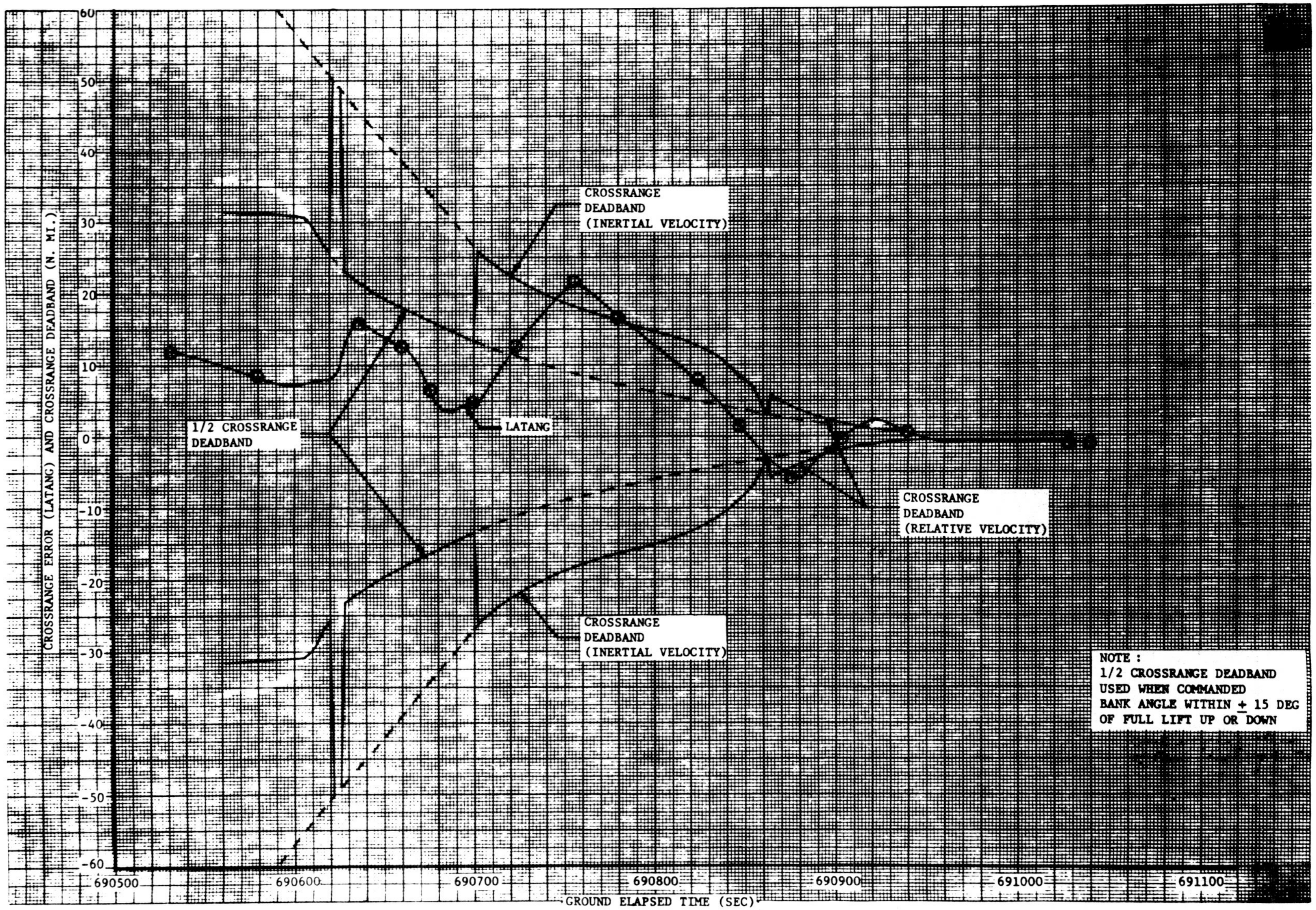

Figure 8. Comparison of the Crossrange Error and Deadband Computed By the Actual CMC to the Simulated CMC

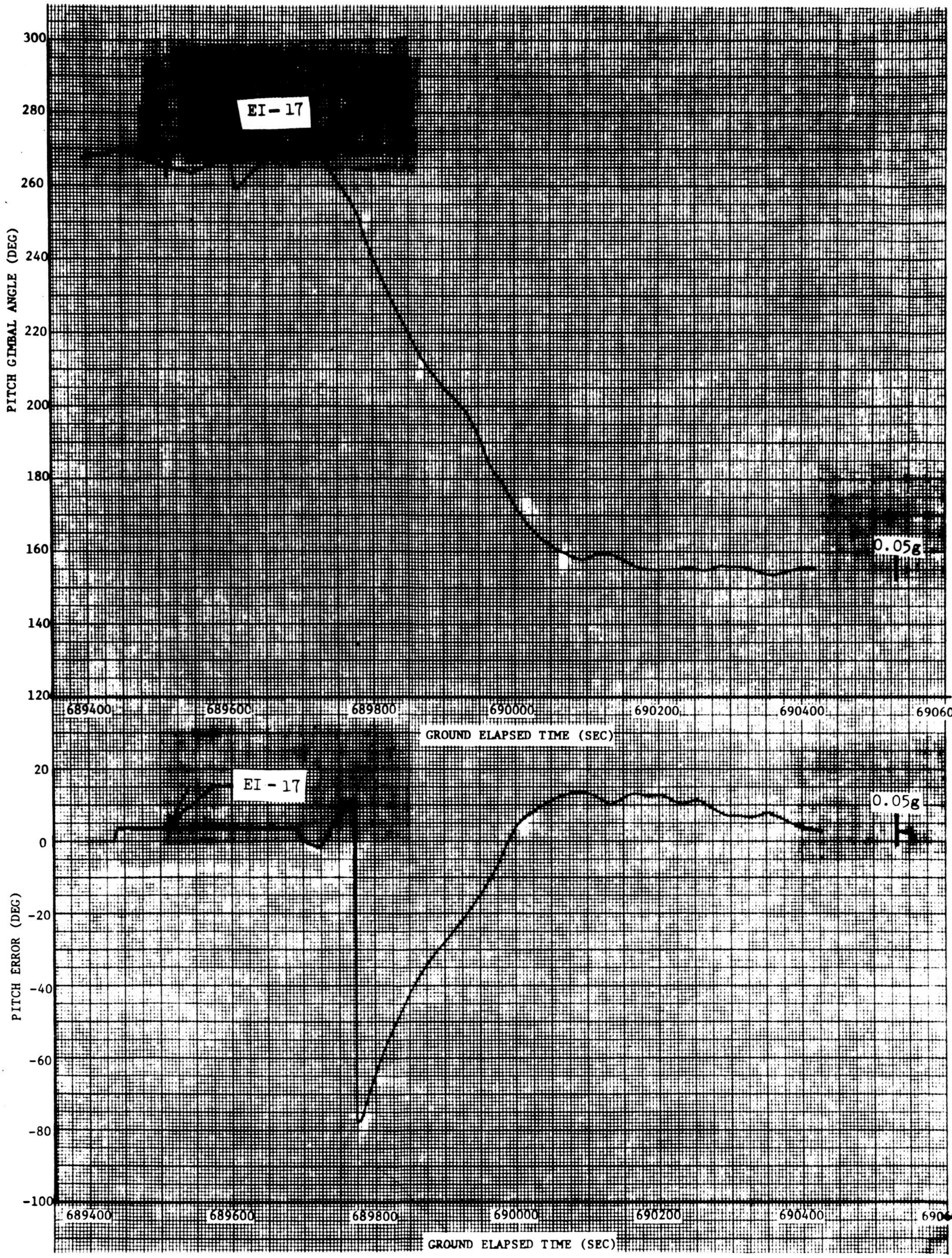

Figure 9. Pitch Gimbal Angle and Pitch Error Versus Time

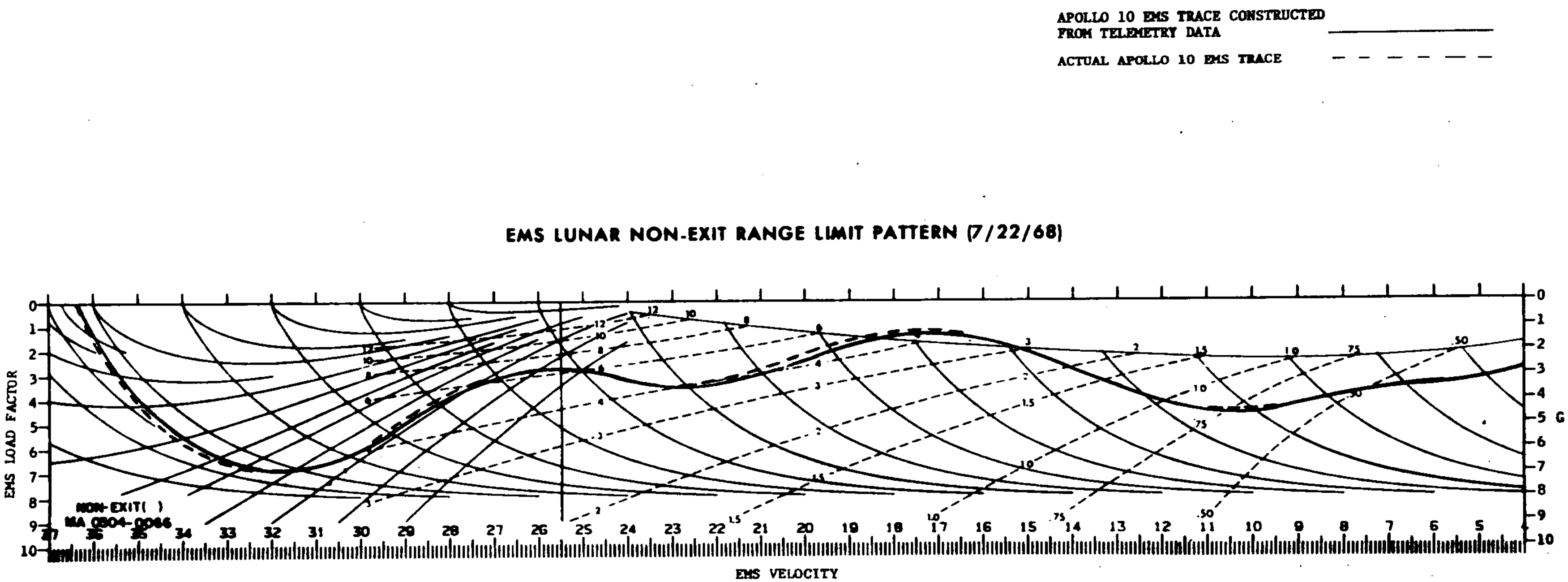

Figure 10. Flight Monitor Trace For Apollo 10

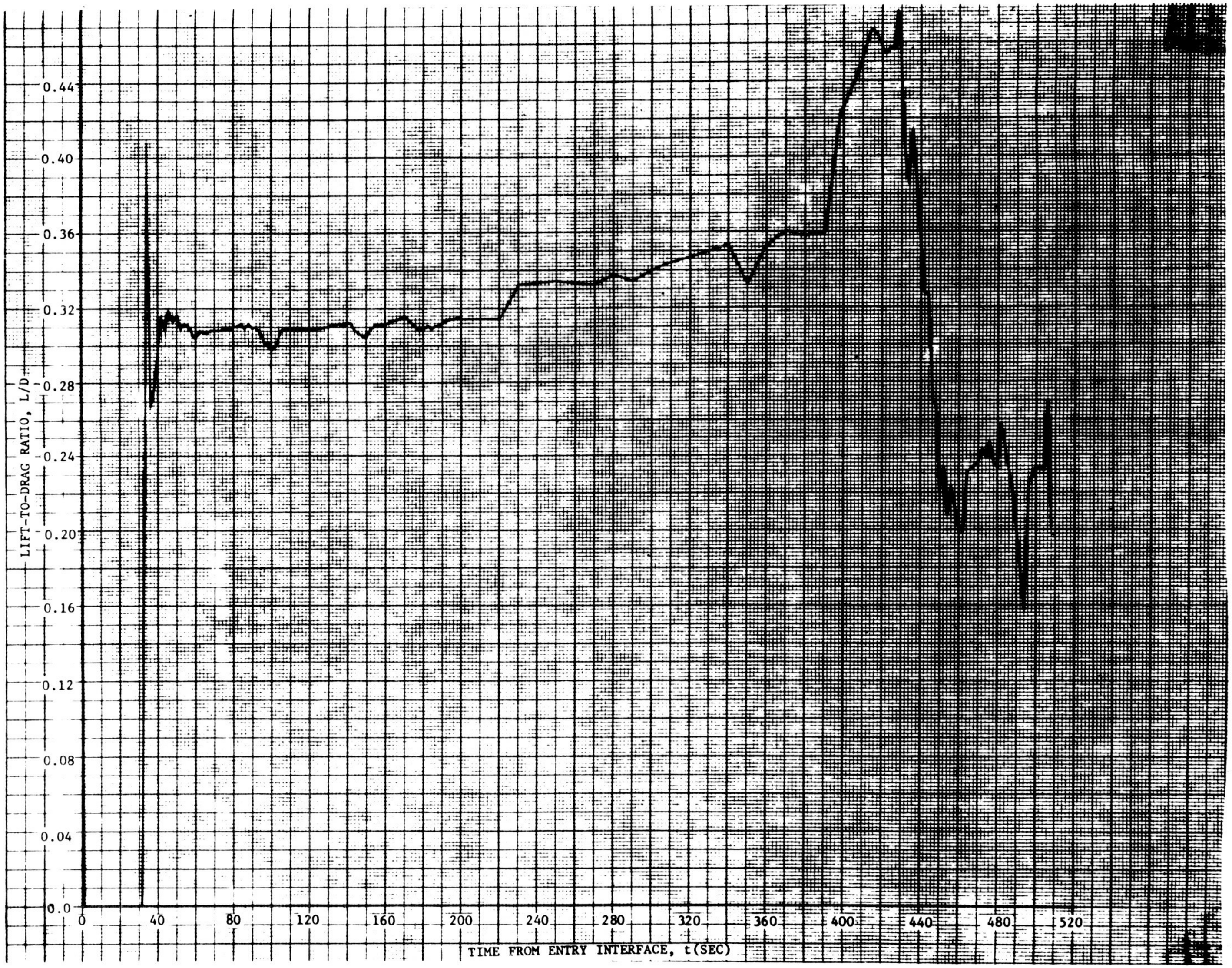

Figure 11. Actual Apollo 10 Inflight L/D Time History

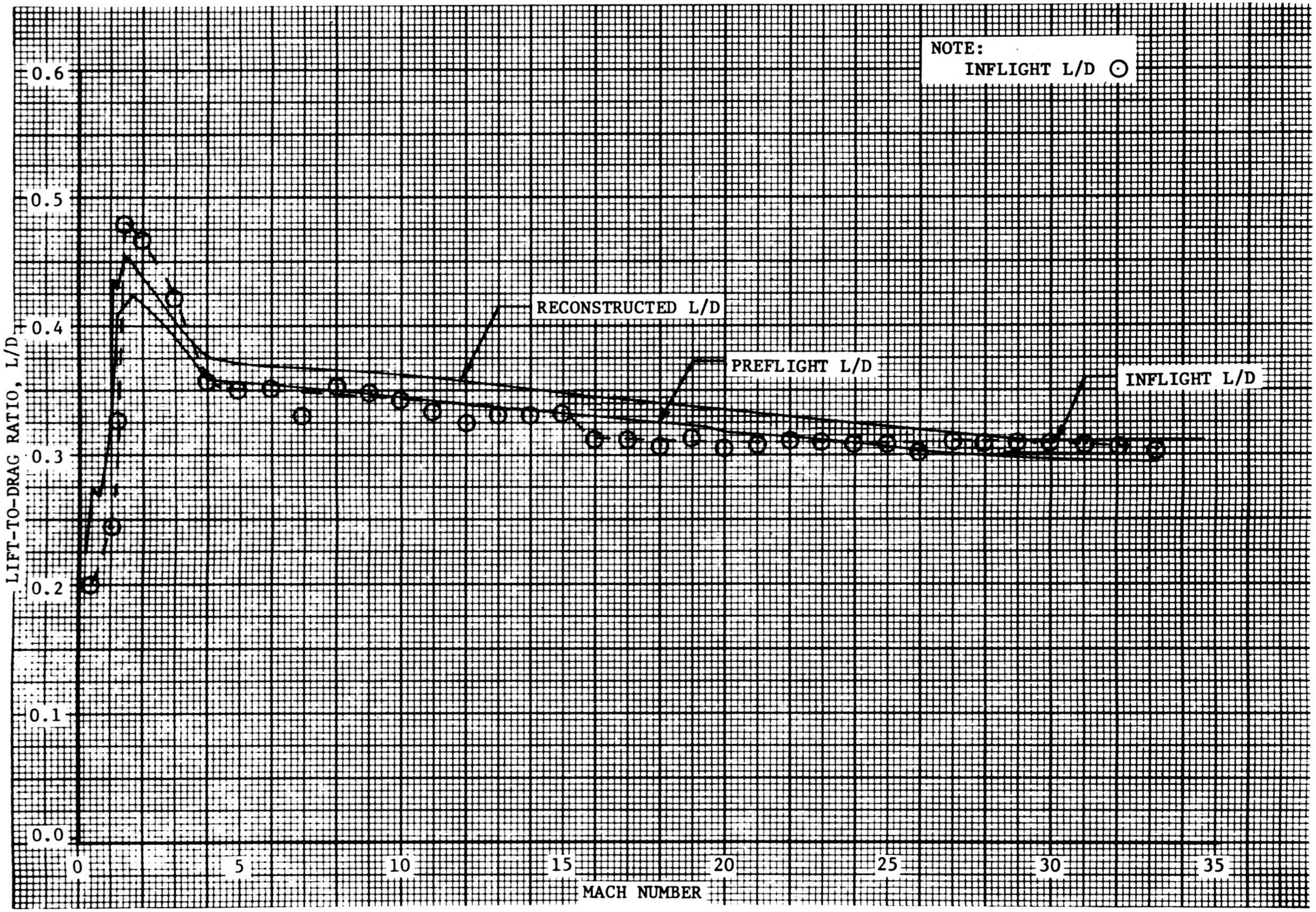

Figure 12. Comparison of the Inflight Measured L/D to the Reconstructed L/D and the Preflight L/D

Figure 13. Comparison of the Apollo 10 Roll Gimbal Angle and the Simulated Roll Gimbal Angle

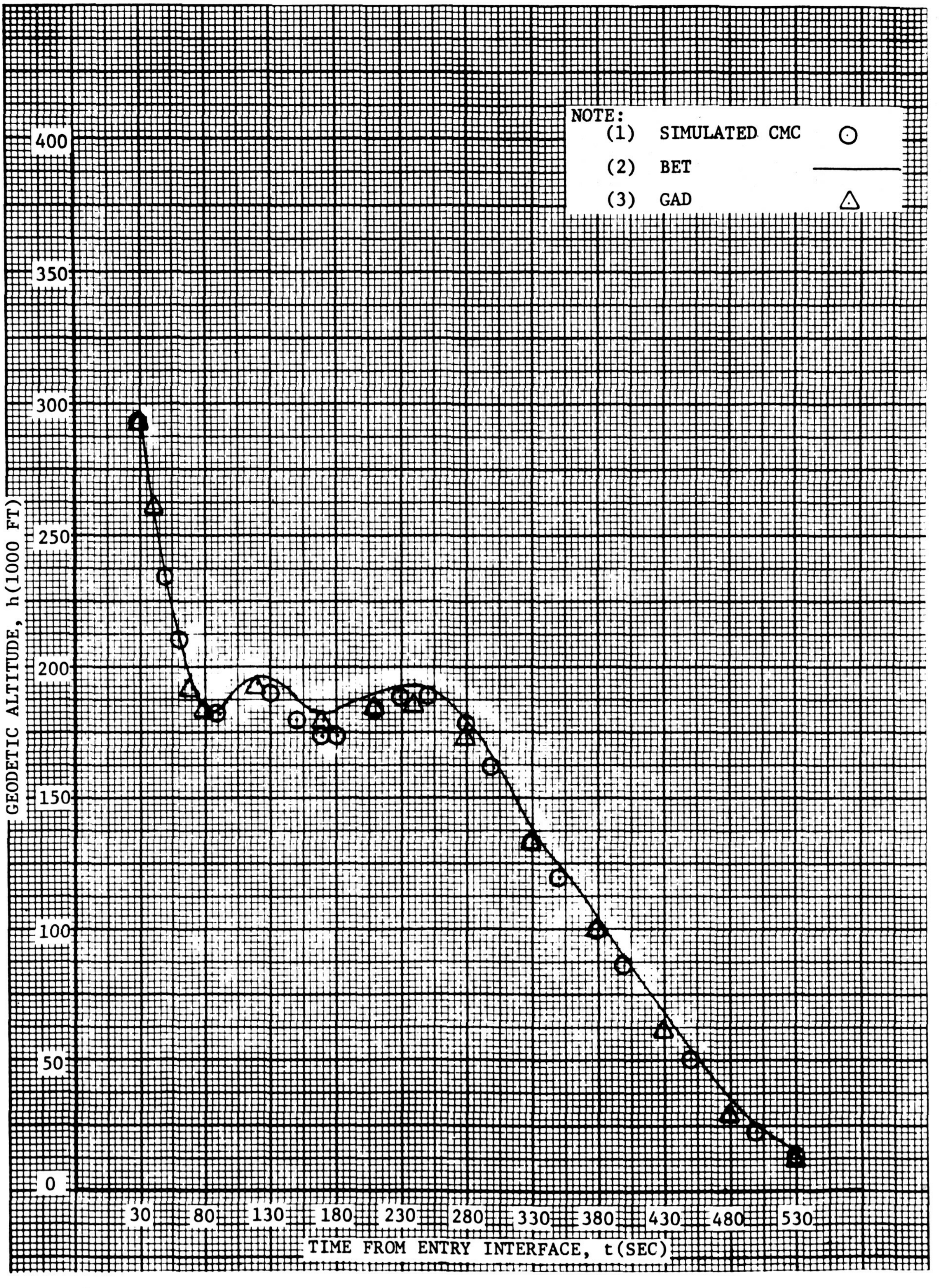

Figure 14. Comparison of the BET Altitude History to the PIPA Environment Trajectory and the Gimbal Angle Drive Trajectory

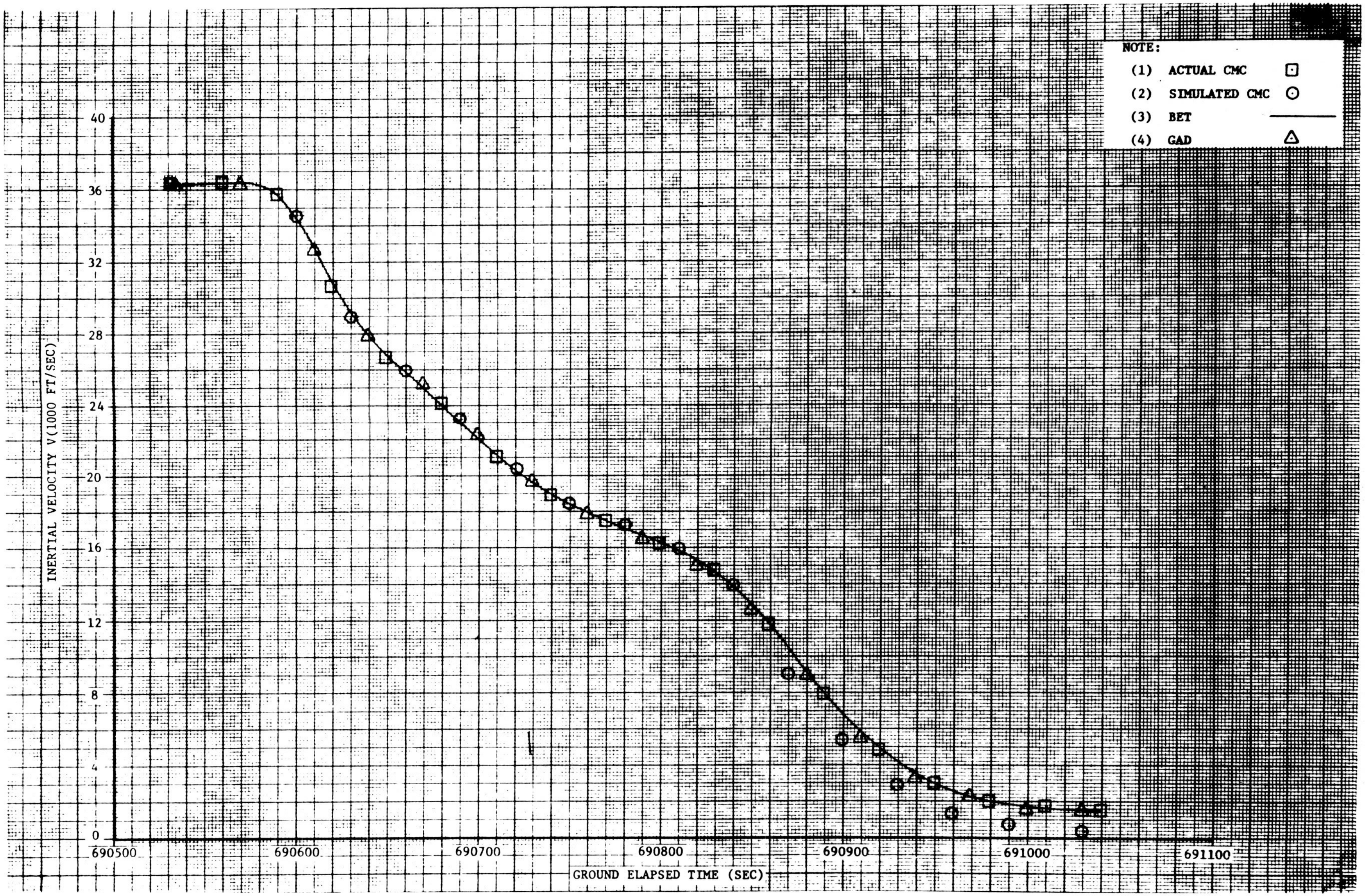

Figure 15. Comparison of the BET Inertial Velocity to the Actual CMC, Simulated CMC and the Gimbal Angle Drive

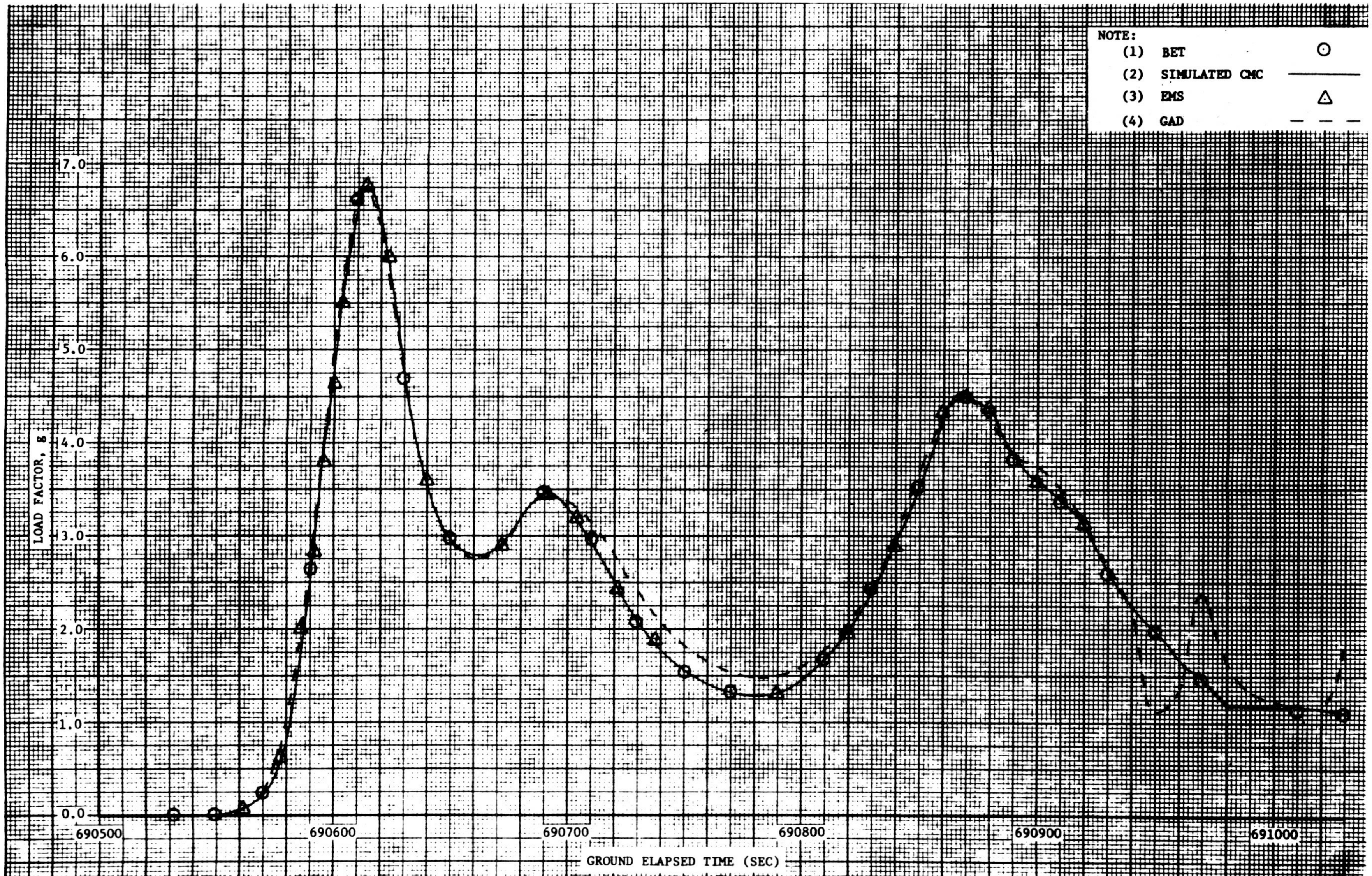

Figure 16. Comparison of the BET, EMS, and GAD Load Factors to the Simulated CMC

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